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# The Study of Phase-shift Super-Frequency Induction Heating Power Supply

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**Abstract**

This paper combines pulse-width phase-shift power modulation with fixed-angle phase-locked-control to adjust the inverter's output power, this method not only meets the work conditions of voltage inverter, but also realizes the large-scale of power modulation, and the main circuit is simple, the switching devices realize soft switching. This paper analyzes the relationship between the output power and phase-shift angle, the control strategy is simulated by Matlab/Simulink, and the results show that the method is feasible and meets the theoretical analysis



*Keywords:*pulse-width phase-shift power modulation; fixed-angle phase-locked-control; induction heating; IGBT; series resonant inverter;

## 1. Introduction

Induction heating power supply is the use of electromagnetic induction principle and Joule's law, it produces Joule heat to make the work-piece heated, it can be used in metal melting, diathermy, heat treating and welding[1].At present, most induction heating applications have higher requirements on heating characteristics、 heating efficiency. Different work-pieces have different heating requirements, so it should be able to control the output power and operating frequency of the inverter[2][3].

According to the structure of induction heating power supply, the power regulation technology can be divided into two kinds, one is rectifier-side power regulation technology(RS-PRT), and the other is inverter-side power regulation technology[4](IS-PRT).

IS-PRT should be adopted in series-resonant inverter. It mainly includes Pulse-Frequency-Modulation(PFM), Pulse-Density-Modulation(PDM), Pulse-Width-Modulation(PWM)[5][6].

In practice, we usually use the pulse-width phase-shift (PW-PS) modulation technology to regulate the

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output power of the inverter, it combines pulse-shift modulation with PWM, together with phase-locked-control circuit.

## 2. Analysis of Pw-Ps Modulation

The main circuit used in this paper is shown in Fig. 1.

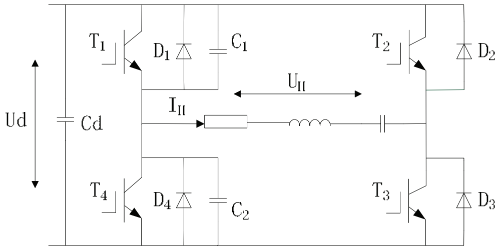


Figure 1. The main circuit of series resonant inverter

As fixed bridge arms, there is a phase difference of 180° between the drive pulses of $T_2$ and $T_3$. $T_1$ and $T_4$ are called phase-shift bridge arms, and the respective drive pulses are ahead of $T_3$ and $T_2$ by phase-shift angle $\beta$, $\beta$ can be adjusted within the range of 0°-180°，When $\beta$ is 0°, the pulses of $T_2$ and $T_3$、$T_1$ and $T_4$ are complementary, each one turns on 180°，by adjusting the control circuit ,the pulses of $T_1$ and $T_4$ are shifted, it makes the drive pulses of $T_1$ and $T_4$、$T_2$ and $T_3$ have a phase difference, and then the tank voltage is no longer a 50% duty cycle square wave, but there is a short time that the voltage is zero, the time will be changed by adjusting $\beta$, it will change the RMS value of tank voltage, so the output power will be changed. Two buffer capacitors are paralleled to super forearm, the four switches achieve soft-switching through the capacitor’s charging and discharging. The following is concrete analysis.

Mode 1. $C_1$ is fully discharged, $C_2$ is charged, $T_1$ and $T_3$ are conducting, the tank voltage is $U_d$, and the tank current increases gradually from zero.

Mode 2. $T_1$ is turned off under ZVS as $C_1$ has fully discharged, C2 begins to be discharged, and the discharge circuit is $C_2$-R-L-C-$T_3$-$C_2$，$C_1$ begins to be charged, and the charge circuit is $U_d$-$C_1$-R-L-C-$T_3$-$U_d$. The capacitors’ charging and discharging is completed during the dead time.

Mode 3. Mode 3. T4 is turned on to meet ZVS as C2 has fully discharged, at this point the direction of current is still positive, and it continues to flow through $T_3$、$D_4$, the circuit is $D_4$-R-L-C-$T_3$，the tank voltage is zero.

Mode 4. $T_3$ is turned off to meet ZCS as the current gradually decreases to zero. The current continues to flow through $D_2$、$D_4$, the freewheeling loop is $U_d$-$D_4$-R-L-C- $D_2$-$U_d$.

Mode 5. $T_2$ is turned on to meet ZCS, because T4 is conducting, the current loop is $U_d$-$T_2$-C-L-R-$T_4$-$U_d$, and the tank voltage is $-U_d$.

Mode 6. T4 is turned off under ZVS as C2 has fully discharged, the current flow process is symmetric with the mode 2’s. Here won’t repeat it.

In summary, the capacitors $C_1$ and $C_2$ charging and discharging rapidly through switches and load circuit, it makes $T_1$、$T_4$ achieve ZVS, and $T_2$、$T_3$ achieve near ZCS, it reduces the semiconductor devices’ switching losses using fewer capacitors.

As the voltage inverter requires the tank current lags the tank voltage by a certain phase value[7]. In this paper, $T_1$、$T_4$ are triggered early, then the pulses front of $T_2$、$T_3$ is the front of the tank voltage, it must ensure the pulses of $T_2$、$T_3$ to keep ahead of tank current a fixed angle, so PLL control circuit must be added.

## 3. Design of Pll Control Circuit

In this paper, PDI XOR phase detector (PD) is used. PLL control block diagram is shown in Fig. 2. It chooses the load resonant current $I_H$ as the locked input signal, as the PLL used XOR PD requires that the phase difference of two signals inputted to XOR is 90° when the two output signals' phase difference is 0°. We make the output of VCO inverted, and the frequency half, make the drive pulses reflected $T_2$、$T_3$ feedback to PD through the delay compensator, and then the PD outputs pulse signals corresponding to phase difference. The LPF outputs a DC voltage which reflects tank voltage and current's fundamental phase shift, it compares with a value which is set representative of a certain phase angle, and outputs a control voltage through PI regulator, then regulates the frequency of VCO, after the half-frequency、dead formation circuit and drive circuit, the conduction frequency of the switches is regulated, then the purpose of automatic frequency tracking is achieved.

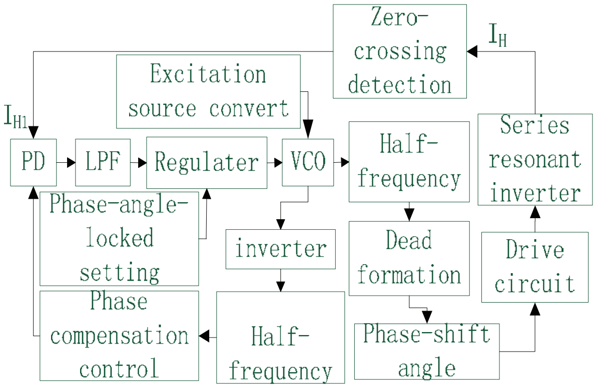


Figure 2. PLL control block diagram

It is the drive pulse forming module of four switches in Fig. 3, a delay circuit is added to $T_1$、$T_4$, the load output power can be changed by adjusting delay time.

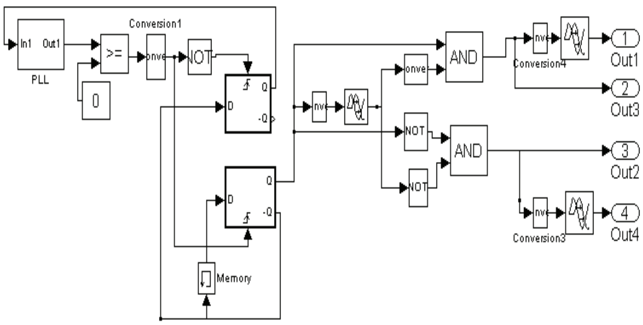


Figure 3. drive pulse forming module

## 4. Analysis of the Relationship Between the Output Power And β

Based on the control method selected in this paper, we assume that the tank voltage is a square wave, its amplitude is $U_d$, and then the RMS of fundamental voltage is

$$U_{ab} = \frac{2\sqrt{2}}{\pi} U_d \cos\frac{\beta}{2} \tag{1}$$

Where $\beta$ is the phase-shift angle.

When the phase-locked angle is $\Phi$, the power factor angle is

$$\varphi = \phi + \frac{\beta}{2} \tag{2}$$

The inverter's load equivalent impedance is

$$Z = \sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2} = R\sqrt{1 + \tan^2 \varphi} = \frac{R}{\cos\varphi} \tag{3}$$

The RMS value of the tank voltage is

$$I_{ab} = \frac{U_{ab}}{Z} = \frac{2\sqrt{2}U_d}{\pi R}\cos\frac{\beta}{2}\cos(\phi + \frac{\beta}{2}) \tag{4}$$

The output power is

$$\begin{aligned} P &= U_{ab} I_{ab} \cos\varphi \\ &= (\frac{2\sqrt{2}U_d}{\pi})^2 \frac{1}{R}\cos^2\frac{\beta}{2}\cos^2(\phi + \frac{\beta}{2}) \end{aligned} \tag{5}$$

Where $U_d$ is the output power of inverter, R is the resistance of the tank, $\beta$ is the phase-shift angle, $\phi$ is the phase-locked angle.

Because the range of $\beta$ is 0°-180°, from this formula，we can see that the output power gradually decreases as $\beta$ increases.

## 5. Analysis of the Simulation Result

The simulation model of IGBT series resonant inverter based on MATLAB/Simulink is established, because the big capacitor as the input of the inverter is equivalent to a voltage source, a DC voltage is used in this model, and the value is set to 400V, take the load resistance R=1Ω, inductance L=25μH, capacitor C=0.4μF, then the quality factor is about 7.9, take these data into the output power formula(5),and make the formula entered into MATLAB, then run it, we can get relationship curve of the output power and $\beta$ which is shown in Fig4. From the simulation, we can see that as $\beta$ gradually increases, the RMS value of tank voltage will decrease, the frequency of the inverter will increase, and the tank current will decrease, then the output power will be changed. The method actually combines the pulse-frequency-modulation. Fig. 5 shows when $\beta$ is 0°, the tank voltage and current waveforms. Fig. 6 and Fig. 7 respectively show when the $\beta$ is 60° and 90°, the tank voltage and current waveforms. We can see that as $\beta$ increases, the time when the tank voltage is 0 grows, that is the RMS value of the tank voltage decreases, the peak value of the current gradually decreases, we can see that the output power gradually decreases, the result is consistent with the theoretical analysis in Fig. 4, and shows that the control method is correct and reasonable in theory.

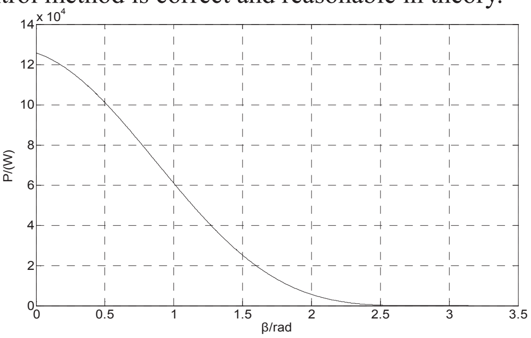


Figure4. The relationship curve of the output power and $\beta$

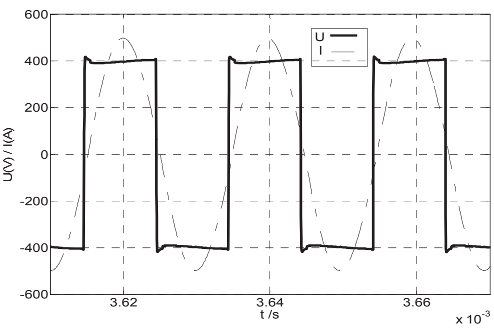


Figure 5. Tank voltage and tank current, β=0°

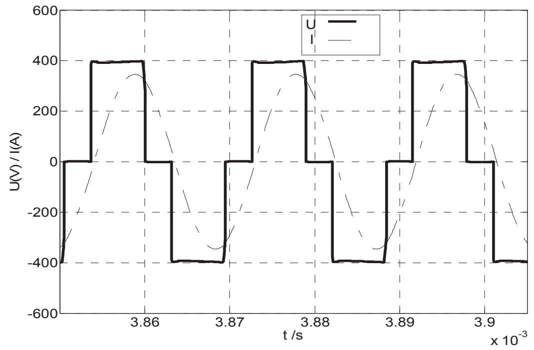


Figure 6.Tank voltage and tank current, β=60°

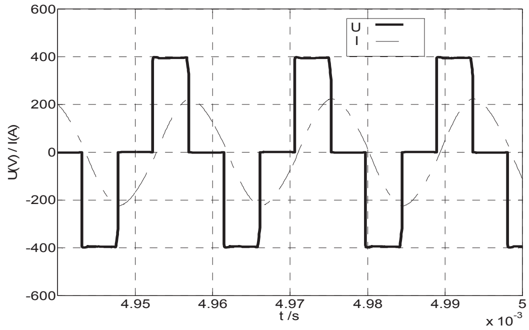


Figure 7. Tank voltage and tank current,

Fig. 8 and Fig. 9 show experimental waveforms of the inverter operating at different phase-shift angles, when the switches turn on, the current is 0, the reverse current continues to flow through freewheeling diode, it decreases to 0 gradually, then the current through the switches increases from 0 to achieve ZCS. when the switches turn off, due to its parallel capacitor has been discharged within the dead time, so the switches achieve ZVS.

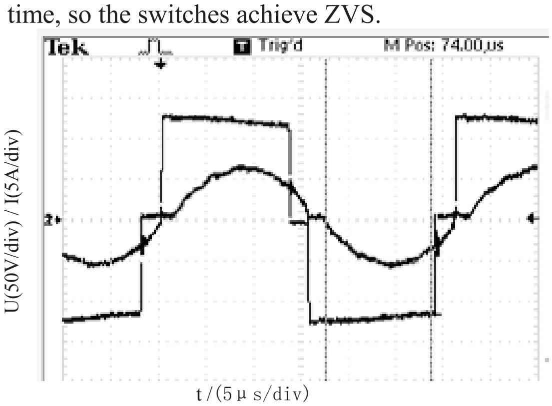


Figure 8. Tank voltage and current, β=23.2°

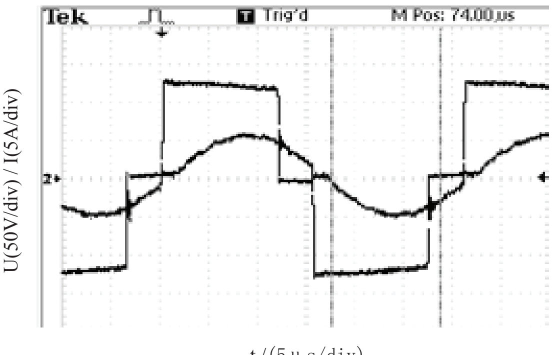


Figure 9. Tank voltage and current, β=42°

## Summary

In this paper, the PW-PS modulation combines fixed-angle phase-locked control method; it ensures the tank current lags the tank voltage by a certain phase value. From the simulation result, we can see that the tank current will change when $\beta$ is adjusted, therefore, the adjustable range of the power is big, while the changes of the frequency is very small, the switches also achieve soft switching, the experiment shows that the control performance is excellent.

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